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A NOTE ON THE VERTICAL STRUCTURE OF A TYPHOON

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[Manuscript received August 2, 1951]

INTRODUCTION

Discussion of the vertical structure of tropical cyclones usually takes the form of a presentation of a cross section through a disturbance. Until quite recently the relevant data were not available, and cross sections published more than 2 or 3 years ago may be taken to represent merely the fantasies of individual writers. However, Simpson [1] had at his disposal sufficient aerological material to draw a cross section through a hurricane which passed over Tampa, Fla., October 7–8, 1946. Subsequent cross sections have been published by Palmén [2] and Arakawa [3], who presents an analysis of the typhoon, *Kitty*, which passed over Tokyo on August 31, 1949.

The cross-section type of presentation provides a graphic picture of hurricane structure, but for some purposes it might be considered preferable to use a parametric form of presentation, such as has been discussed by the present writer (unpublished). In essence what is studied is the total pressure drop (intensity) to the center of the disturbance at a given height, this being a measure of the mean pressure gradient within a vortex of specified horizontal scale. The vertical structure is defined by the way in which the intensity changes with height.

An alternative approach is to examine the vertical structure of the central contour anomaly, or difference in contour height of a given pressure surface between the center and the periphery of the vortex. The contour anomaly is, of course, proportional to the pressure drop divided by the density at the relevant level, so that both modes of presentation are equivalent. Which parameter we select is largely dependent on whether the raw aerological material quotes contour heights or pressure at fixed levels.

The parametric approach has been employed (James [4]) to determine the structure of a hurricane which passed over Tampa, Fla., on October 19, 1944 (Simpson [5]). The vertical structure of this disturbance was found to be quite simple; the intensity decreased with height up to about 3 km. The decay was approximately exponential. Above 3 km. an exponential decay was observed, with a more rapid decay rate. The decay in the lowest range was such that the central contour anomaly remained almost constant with height, that is to say, the lowest 3 km. of the vortex was *barotropic* in structure.

Arakawa [3] has published a number of aerological ascents taken at Tokyo during the passage of *Kitty*. We propose here to use this material to investigate the structure of *Kitty*, and to compare it with that for the Tampa hurricane of October 19, 1944.

THE PRESSURE DROP

The radiosonde ascents taken at Tokyo on August 30, 1230 hr. (local time) and on September 1, 1100 hr. may be taken to refer to the periphery of the typhoon in front and rear respectively. The mean of these two soundings has been taken as a typical periphery ascent. The ascent at 1849 hr. on August 31 was made just in advance of the eye passage, and may be taken as typical of the center of the disturbance. The pressure difference between periphery and center (intensity), plotted on a logarithmic scale against height, is shown in figure 1.

It will be noted that log intensity decreases approximately linearly with height up to about 9 km., the decay being given by

$$h = h_o \exp(-z/9.5)$$

where z is the height expressed in km., h is the pressure drop from periphery to center at height z, and h_o is the surface pressure drop. Above 9 km. the decay is more rapid, approximately as $\exp(-z/4.3)$. Above 12 km. the scatter becomes pronounced. We cannot be sure of the

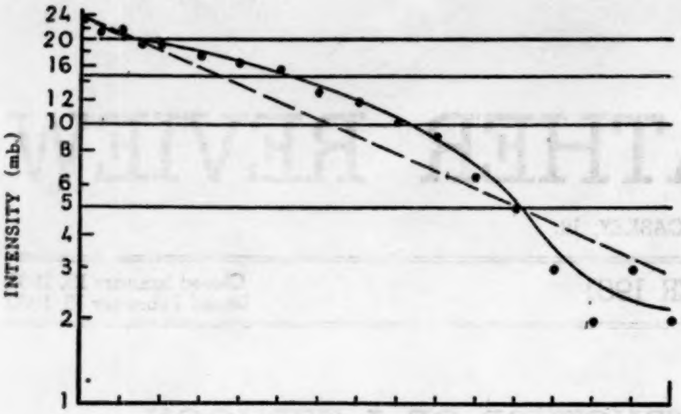

FIGURE 1.—Intensity (logarithmic scale) as a function of height in the typhoon *Kitty*.

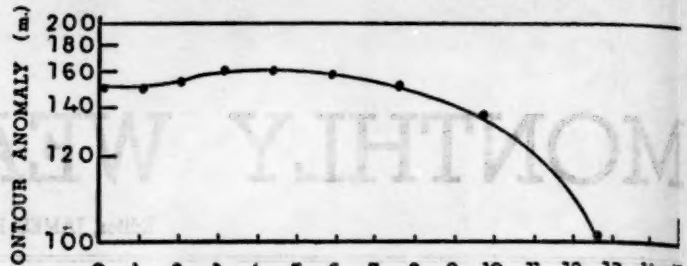

FIGURE 2.—Contour anomaly (logarithmic scale) as a function of height in the typhoon *Kitty*.

accuracy of the ascents at these high levels, where it will be observed, the pressure drop, known only to the nearest millibar, is of the order 2–3 mb. only.

In the Tampa hurricane of October 19, 1944, the writer found an exponential decay as $\exp(-z/9.5)$ up to 3 km., and a decay as $\exp(-z/4.2)$ above that level.

In both cyclones two characteristic and almost identical decay rates are in evidence. The Lows differ in that the slow decay rate holds in the Tampa hurricane up to 3 km. only, whereas in *Kitty* this rate applies up to about 9 km.

It requires analysis of further hurricanes to establish whether this exponential decay at two characteristic rates is a general structural property, but an analysis of mean hurricane soundings published by Schacht [6] suggests that it is.

It would seem then that the vertical structure of hurricanes can be specified by two characteristic decay rates, together with the transition height from one to the other. The vertical structure may, however, be specified more crudely by fitting a single decay curve throughout the range. As a parameter we used the equivalent height, Z (James [7]), defined by

$$h_o Z=\int_0^\infty h\, dz.$$

The vortex with the one decay rate

$$h=h_o \exp(-z/Z),$$

with the same equivalent height as the actual vortex is termed the *equivalent vortex*. It is indicated by the dashed line in figure 1. It will be seen that the equivalent vortex gives a very approximate fit to the vertical profile of intensity, but that the fit with two decay rates is emphatically better

The equivalent height of *Kitty* is 7.1 km. That found for the Tampa hurricane was 5.5 km., reflecting the shallower nature of this disturbance.

THE CONTOUR ANOMALY

The equivalence of the contour anomaly and the pressure drop or intensity for specifying vertical structure was mentioned in the introduction, and examination of structure by means of the contour anomaly introduces an important new feature.

Figure 2 shows the difference in contour height between the periphery and the center of *Kitty* for a number of pressure surfaces. The change in contour anomaly with height amounts only to a few percent in the first 8 km. At higher levels the anomaly drops rapidly.

The layer with nearly constant contour anomaly corresponds to the range in which the intensity falls off as $\exp(-z/9.5)$, while the region of decreasing contour anomaly corresponds to the more rapid decay of h.

The conspicuous structural feature of *Kitty* revealed by a study of the contour anomaly is that the vortex is nearly *barotropic* in the lowest range. It was found (James [4]) that the Tampa hurricane was barotropic, but in a more restricted range, up to 3 km. Lower level barotropy was also found in Schacht's mean hurricane soundings. It may, therefore, be regarded as a structural property of hurricanes, although the depth of the barotropic layer varies in different disturbances.

In a barotropic vortex no work can be done by taking an air-parcel around a closed circuit, for

$$\oint \frac{dp}{\rho}=0. \qquad (1)$$

Arakawa [3] has shown the barotropic nature of *Kitty* in the lower layers by evaluating the integral (1) for various circuits. The solenoidal field only becomes appreciable above 400 mb.

It is possible for a vortex to show over-all barotropy and yet still have an intense concentration of solenoids, acting in different senses in different parts of the field. This is not found to be the case with *Kitty*; her contour gradient is approximately constant with height in different parts of the field.

THE WIND FIELD

In a steady-state vortex we should anticipate a one to one correspondence between contour gradient and wind speed. In a *geostrophic* vortex the wind speed is proportional to the contour gradient. If we neglect the Coriolis parameter altogether, and consider a *centrifugal* vortex, the velocity squared over the radius of curvature of path is proportional to the contour gradient. In a hurricane we should expect an intermediate law of variation of wind with contour gradient. However, whatever the relation connecting wind and gradient, if the mean contour gradient is invariant with height, so also will be the wind speed.

The wind profiles of *Kitty* do not exhibit this constancy with height in the barotropic layer. The broadly characteristic wind profile is of a decrease of wind up to 2–4 km., with a subsequent increase. Thus, for example, at 1220 hr. on August 31, there was a maximum speed at 0.9 km. (090° 18 m/sec), a minimum at 3.4 km. (180° 2.8 m/sec), and another maximum at 5.4 km. (126° 17 m/sec). The typhoon shows no direct correspondence between wind and contour gradient profiles.

It may be remarked that a typhoon is not a steady-state system in which a one to one correspondence between wind and pressure fields may be expected. This, however, does not entirely solve the puzzle. Neglected terms in the equations of motion may be of vital importance. Durst and Sutcliffe [8] have pointed to the importance of the vertical velocity term, $w\partial v/\partial z$, in the equation of motion in the determination of the horizontal wind field in a tropical cyclone. It may be possible to conceive of a pattern of ascent which could determine the wind field irrespective of the pressure gradient. It might appear, therefore, that the dynamics of hurricanes presents highly complex problems for which there is no solution immediately in sight.

CONCLUSIONS

Whatever the theoretical uncertainties a broad morphological pattern for tropical Lows is becoming increasingly manifest.

In its lowest layers a hurricane appears to be almost barotropic in structure, the depth of the barotropic layer varying, perhaps, between 3 km. and 9 km. or more. Above this layer is a region in which pressure and contour gradients decay exponentially with height, at a rate which appears to be characteristic for a number of disturbances.

It is of interest to note that Goldie [9] and James [4] both find a constant momentum layer characteristic of occluded extratropical Lows (as of warm Highs), the limiting height being of the order 8–9 km. Exponential decay is found to be characteristic above the equimomental layer, with decay rates close to that found in our two tropical Lows. There thus appears to be a similarity in the vertical structure of tropical and mature extratropical disturbances.

No information is available touching the question of an evolutionary change in the vertical structure of hurricanes.

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THE WEATHER AND CIRCULATION OF NOVEMBER 1951[1]

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The month of November 1951 was notable for its early cold weather in most of the United States. Chart I-B shows that average temperatures for the month were below the long-period normal in all parts of the country except for the far West and portions of New England and the Rocky Mountain States. The greatest departures from normal (over 8° F.) occurred in Wisconsin and Minnesota, while the lowest temperatures in an absolute sense were found in northern Minnesota and North Dakota, where the temperature averaged 17° F. (Chart I-A). This was the coldest November on record at Green Bay, Wis., South Bend, Ind., and Dubuque, Iowa. November's temperature regime contrasts with the pattern observed during the preceding month, when the temperature averaged well above normal throughout most of the eastern and southern halves of the Nation [1]. Only in sections of the Southwest, Northern Plains, and Pacific Coast did October's temperature anomaly persist through November. In nearly all other regions large changes occurred. Such pronounced differences between the temperature anomalies of adjacent months have been more frequent from October to November than between any other pair of months during the past decade [2].

[1] See Charts I-XV following p. 214 for analyzed climatological data for the month.

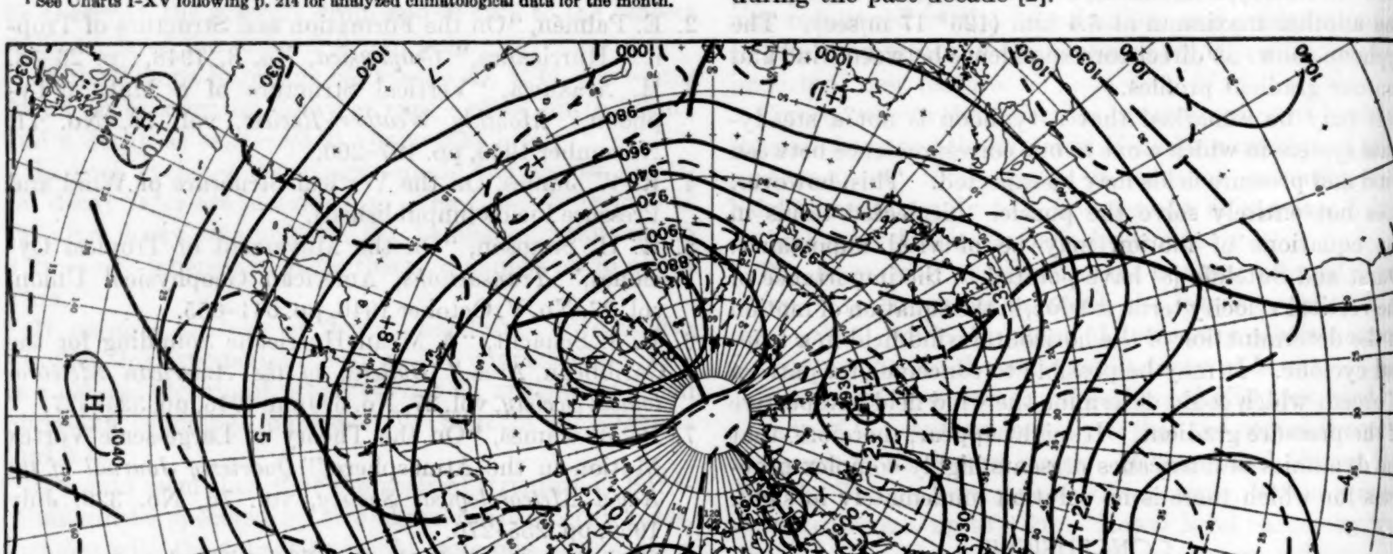

FIGURE 1.—Mean 700-mb. chart for the 30-day period October 31–November 29, 1951. Contours at 200-foot intervals are shown by solid lines, intermediate contours by lines with long dashes, and 700-mb. height departure from normal at 100-foot intervals by lines with short dashes with the zero isopleth heavier. Anomaly centers and contours are labeled in tens of feet. Minimum latitude trough locations are shown by heavy solid lines.

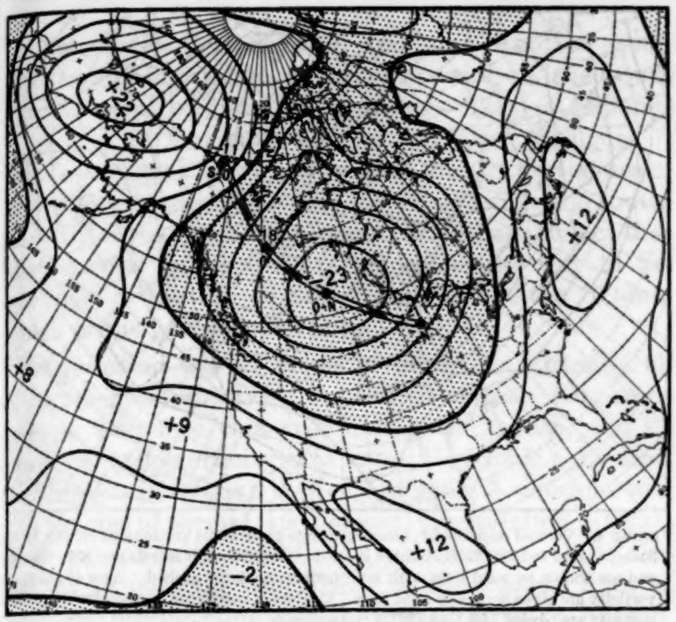

FIGURE 2.—Mean thickness anomaly for the layer between 1,000 and 700 mb. for the 30-day period October 15–November 14, 1951. Isopleths are drawn at 50-foot intervals with the zero isopleth heavier, and centers are labeled in tens of feet. Negative values are shaded. Arrows indicate track of principal negative anomaly center as determined from four consecutive 30-day mean charts. The intensity in tens of feet is plotted above each position of the center, and the 30-day period encompassed is plotted below (e. g., O stands for October. O-N for mid-October to mid-November, etc.).

November's cold weather was closely related to the presence of a monthly mean trough at all levels of the troposphere extending from the Mississippi Valley through James Bay to Baffin Island (Charts XII to XV). This trough was located west of its normal position along the Atlantic coast and was considerably deeper than normal over practically the entire United States, with greatest departures in Minnesota (fig. 1), where the weather was coldest. On the other hand, 700-mb. heights averaged above normal in Alaska and western Canada, where a ridge was located. Between this ridge and the trough in the Mississippi Valley currents of deep cold air flowed southeastward in repeated surges throughout the month. Each of these surges was accompanied by the movement of a polar anticyclone from its source region in northwestern Canada southeastward into the United States (Chart IX). The most severe and widespread cold wave of this type occurred during the first week of November, when new records for early season low temperatures were set in over a dozen states from the Great Basin to the Atlantic coast.[2]

It is probable that November's cold would not have been so extreme if temperatures in Canada had been near normal. Objective estimates of the temperatures in the United States based on the observed 700-mb. circulation pattern alone would call for near-normal temperatures in most of the country. The reason for this discrepancy is believed to be the recent temperature distribution in western and central Canada. In this region, the source for most of the polar continental air affecting the United States, temperatures were far below normal throughout the months of October and November. This condition was most pronounced during the 30-day period from mid-October to mid-November as illustrated in figure 2. As a result the Canadian air which invaded the United States at frequent intervals during the month was abnormally cold at its source, and temperatures in the United States were lower than would normally be expected from the observed circulation alone. It is pertinent that the center where the coldest air relative to normal was found appeared to move steadily southeastward on the monthly mean charts, from the Arctic coast of Canada in September–October to Minneapolis, Minn., in November, along the track indicated in figure 2. A study of the factors responsible for this remarkable migration and its relation to Canadian surface temperature, snow, and ice is planned.

The only State unaffected by the recurrent cold air outbreaks was California, where temperatures remained above normal during all but the last week of the month. This area, as well as portions of adjoining States, was dominated by mild Pacific air transported by stronger-than-normal southwesterly flow at both 700 mb. (fig. 1) and sea level (Chart XI). Temperatures also averaged above normal in eastern New England, as mean wind components from the south were much stronger than normal at both sea level and 700 mb. Near-record high temperatures occurred in this area on November 14. The only other part of the country with monthly mean temperatures above normal was the northern Rocky Mountain States, where some temperature departures were slightly positive under the influence of rather strong anticyclonic westerly flow at 700 mb.

The anticyclone and cyclone tracks presented in Charts IX and X present a rather chaotic appearance at first glance. The principal tracks have therefore been illustrated schematically in figure 3, where they are superimposed on the field of relative vorticity computed from the monthly mean 700-mb. contours (fig. 1). The schematic tracks were prepared on the basis of the daily Northern Hemisphere maps analyzed regularly in the Extended Forecast Section of the U. S. Weather Bureau, as well as Charts IX and X. As expected, the tracks largely follow the steering current of the mean 700-mb. flow. However there is also a marked tendency for many of these tracks to lie along the major axes of cyclonic and anticyclonic vorticity, as previously noted [3]. This relationship is indicative of the fact that the field of relative vorticity at 700-mb. is generally a good index of the monthly mean sea level pressure pattern. For example, centers of anticyclonic vorticity at 700 mb. in figure 3 are nearly superimposed on centers of high pressure at sea level (Chart XI) in the Great Basin, southwest Pacific, central Atlantic, northwest Canada, and northern Greenland. Likewise, centers of cyclonic vorticity and low pressure almost coincide in the vicinity of the Bering Sea, Gulf of Alaska, Davis

[2] Further details about the early November cold wave can be found in the following article by Carr and in the December 1951 issue of *Weatherwise* (pp. 131 and 141).

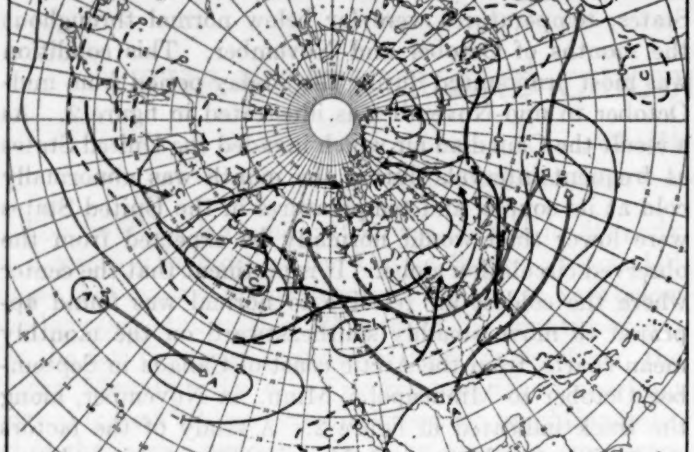

FIGURE 3.—Vertical component of mean relative geostrophic vorticity at 700 mb. for the 30-day period October 31–November 29, 1951, in units of 10^{-6} sec^{-1} with the zero lines dashed. Centers of anticyclonic vorticity are labeled "A" and centers of cyclonic vorticity are labeled "C". Idealized cyclone and anticyclone tracks are indicated by solid and open arrowhead curves respectively.

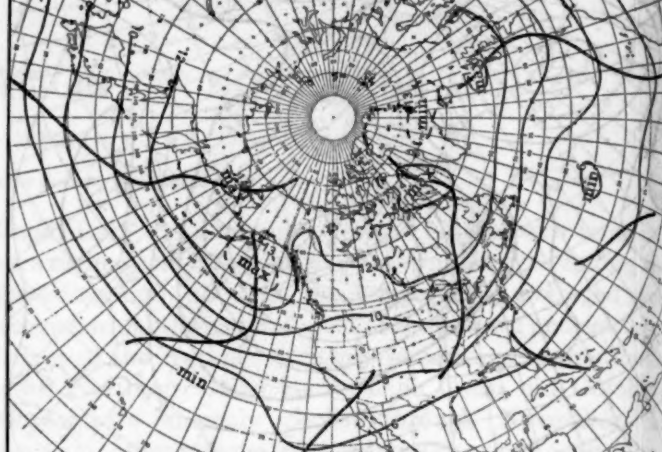

FIGURE 4.—Vertical component of mean absolute geostrophic vorticity at 700 mb. for the 30-day period October 31–November 29, 1951. Isopleths at intervals of 2×10^{-5} per second are shown by solid lines with intermediate isopleths dashed. Axes of maximum vorticity are given by heavy solid lines. Centers of maximum and minimum absolute vorticity are labeled MAX and MIN respectively.

Strait, and northwest British Isles. In these anticyclonic centers migratory high pressure areas on the daily map tended to cluster, intensify, and move in loops, while daily Lows behaved similarly in the cyclonic centers. Cyclonic activity was minimized in the anticyclonic centers, and anticyclonic activity was weak in the cyclonic centers. Thus, in a sense, these centers may be considered as centers of action observed during the month.

The cyclone and anticyclone tracks can be clarified further by reference to the monthly mean chart of absolute vorticity, figure 4. This map was prepared by simply adding the Coriolis parameter to values of the relative vorticity computed for figure 3. It is noteworthy that most of the daily cyclones moved toward regions of higher absolute vorticity, while the anticyclones generally moved toward lower vorticity, in agreement with the theory of vorticity transfer [4]. This principle is helpful in explaining some tracks which crossed the mean 700-mb. contours at rather large angles, such as the anticyclone track along the Rocky Mountains and the cyclone track in the central United States. It can also be applied to tracks which do not lie in the principal channels of relative vorticity, for example, the storm path along the east coast of North America and the anticyclone track through the lower Lakes. The last two tracks intersect in southern New England in a region of zero relative vorticity. This was a region of great interdiurnal pressure variability, where Highs and Lows followed each other in rapid succession, with neither predominating on the monthly mean. A similar condition prevailed along the northern border of the western United States. The anticyclones which traversed the Great Lakes, however, were primarily of the shallow cold type so that cyclonic vorticity prevailed in the mean at the 700-mb. level. It is also interesting to note that the gradients of both 700-mb. height and absolute vorticity were extremely strong to the south of the Gulf of Alaska and near Newfoundland. Within these regions migratory cyclones and anticyclones were numerous and active during the month. These disturbances were effective in transferring the vorticity required for maintenance of the zonal circulation according to Kuo's theory [4].

Since absolute vorticity generally increases in magnitude with increasing latitude, the isopleths in figure 4 are primarily sinusoidal in character. These isopleths tend to parallel the contours of 700-mb. height, which usually decrease with increasing latitude. Therefore axes drawn through points of maximum vorticity along latitude circles generally coincide with trough lines drawn through points of minimum height along latitude circles. Thus the principal troughs in figure 1, in the eastern Atlantic, western Pacific, southeast Pacific, and North America all appear in virtually the same location as axes of maximum vorticity in figure 4. However, the latter chart contains an additional axis of importance, extending from a vorticity maximum in the Gulf of Alaska southwestward to a position just north of the Hawaiian Islands. This feature was reflected in a mean trough at sea level (Chart XI), a weak center of negative height anomaly at 700 mb. (fig. 1), and an abundance of cyclonic activity (Chart X), all of which combined to help produce above normal precipitation in most of the West Coast and adjoining States (Chart III). This vorticity axis also helps explain the asymmetry in figure 1, where the ridge in western North America is much closer to its downstream trough, in North America, than to the first trough upstream, off the coast of Asia. Figure 4 contains a more uniform wave spacing and suggests that the axis of maximum 700-mb. vorticity in the eastern Pacific affected the wave pattern. This points up the limitations in using the somewhat arbitrary definition of a trough as a line connecting the

minimum latitude reached by contours. Another significant axis of maximum vorticity appears off the south Atlantic coast of the United States. This corresponds to an area of maximum contour curvature in figure 1. This feature may have been responsible, in part at least, for the heavy precipitation observed in Florida and southern parts of Alabama and Georgia, as well as the fact that below-normal temperatures extended all the way to the east coast of the United States, well east of the 700-mb. trough in the Mississippi Valley.

Precipitation was in excess of normal in virtually all of the northeast quarter of the United States. Numerous cyclones traversed this area during the month, and its mean 700-mb. vorticity was mostly cyclonic. In fact, the line of zero relative vorticity in figure 3 coincides well with the line of normal (100 percent) precipitation in Chart III-B (except in the middle Atlantic States). It is also relevant to note the coincidence of the western limit of the excess precipitation with the axis of negative 700-mb. height anomaly, approximately along 95° W. In other words, where precipitation was above normal, 700-mb. wind components relative to normal were from the south; while precipitation was generally below normal in sections with 700-mb. flow from a northerly direction, relative to normal. More than twice the normal amount of precipitation fell along the north and middle Atlantic Coast and also in a narrow zonal band from Virginia to Missouri. The coastal precipitation occurred along a principal cyclone track (fig. 3), while the zonal band was located just north of a zone of marked confluence at 700 mb. [5] (fig. 1). Weather highlights associated with these conditions were gusts of 96 m.p.h. at Blue Hill, Mass. on the 3d, tornadoes in the Midwest on the 13th, and local floods in Arkansas on the 24th.

The combination of below-normal temperature and above-normal precipitation resulted in total snowfall well in excess of normal in most of the Northeast and Midwest, with greatest departure (over 16 times the normal amount) in parts of Missouri and adjacent States (Chart V-A). During the first week of the month some sections of the Southern States observed their earliest snowfall on record and many stations in the Midwest had record November 24-hour amounts. The 12.5-inch fall in St. Louis, Mo., on the 6th was the greatest 24-hour fall in that city in the past 39 years. Mild weather during the last week of November resulted in melting most of the month's snowfall, so that northern New England was the only area east of the Rocky Mountains with a deep snowcover on December 4 (Chart V-B).

Except for Colorado, precipitation was generally deficient throughout the Plains and Rocky Mountain States. Dry weather in this area was associated with downslope (foehn) winds since the 700-mb. flow was stronger than normal from the northwest and the principal cyclone track was north of the United States border. Furthermore, this region was traversed by numerous anticyclones during the month, and the mean relative vorticity was strongly anticyclonic. Anticyclonic vorticity was also associated with subnormal precipitation in the West Gulf States and parts of the deep South.

From a hemispheric point of view perhaps the outstanding feature of November's weather was the heavy rainfall in the Po River Valley of Italy. This culminated in the worst flood in North Italy's modern history, with over 150 persons killed and nearly 200,000 made homeless. Some of the meteorological conditions associated with this disaster are illustrated in figure 1. North Italy was located in a region of stronger than normal southwesterly flow at 700 mb., about 800 miles east of a deep mean trough. Such a position has been found to provide the optimum combination of moisture and convergence for heavy precipitation due to cyclonic and frontal activity [5]. In addition, a portion of Italy's rainfall was orographic in nature. It is also important to note that the blocking regime over Europe during October diverted much cyclonic activity to the Mediterranean and produced a closed 700-mb. Low centered over northern Italy [1]. This circulation pattern was favorable for heavy rainfall, thus setting the stage for November's flood.

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GENESIS OF WINTER WEATHER OVER WEST TEXAS

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INTRODUCTION

During the first week of November 1951, a large, cold Low, with a closed center extending to the 200-mb. level, dominated the free air circulation over the eastern half of the United States. This Low, which was elongated to the north and south of the center, lay approximately along the 82d meridian at the 500-mb. level on November 5. Generally speaking, it overlay the Hudson Bay region. (See the preceding article by Klein).

Shallow trough lines formed southwest, or west, from a center (in the major trough) west of James Bay, and moved into the United States from south-central Canada. One such trough on the evening of the 4th, moved southeastward out of Wyoming; it was associated with a snowstorm and two other phenomena whose origins were not immediately apparent.

One effect was the cold weather over the South Central and Gulf States, while the second was the formation of a large inverted "V" ridge of high pressure with a center over west Texas. What made these features interesting was the finding that they did not move directly into the South from the region of Canada, as usually happens. The discussion of these findings fills the major portion of this article. A remaining portion reports on the snowstorm which moved up the Mississippi Valley.

THE AIR FLOW AT THE 500-MB. LEVEL

Early on November 5, a previous surge of cold air was moving off the Atlantic Coast of the United States. At the 500-mb. level the isotherms and contour lines were parallel over the eastern half of the country with strong westerly winds (50 knots or more) over a large portion of the area east of the 95th meridian. So it seemed that the eastern portion of the United States would enjoy a respite from the cold weather which had invaded the length of the Mississippi Valley on the 3d of the month. However, the early morning map for November 5 revealed a developing trough along a line from Huron, S. Dak., through Goodland, Kans., to Albuquerque, New Mex.

The map that evening showed a closed circulation above Wichita, Kans. During the next 24 hours this Low moved toward Columbia, Mo., and then northeastward to a position west of Rantoul, Ill., on November 7 (fig. 1). This development appreciably altered the isotherm arrangement permitting north and south transport of the contrasting air masses. The southward dip of the isotherms over the southwestern plains signified the movement of cold air toward Texas and the Gulf of Mexico. In the following two days, the Low moved northeastward while the isotherm orientation returned to west-east over the eastern half of the country.

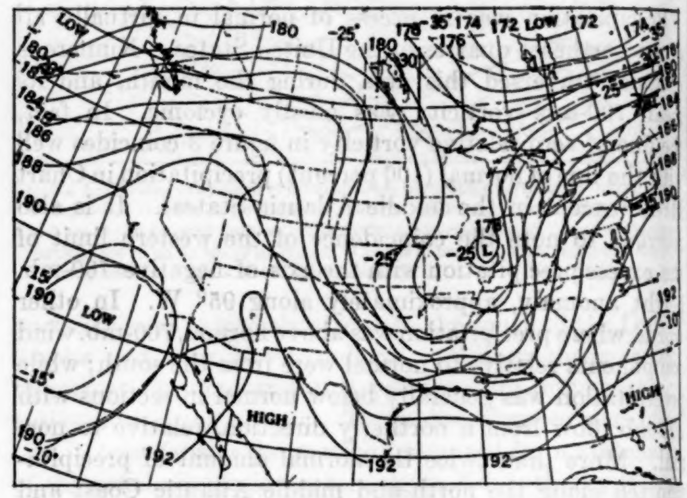

FIGURE 1.—500-mb. chart for 0300 GMT, November 7, 1951. Contours (solid lines) at 200 foot intervals are labeled in hundreds of geopotential feet. Isotherms (dashed lines) are at intervals of 5° C.

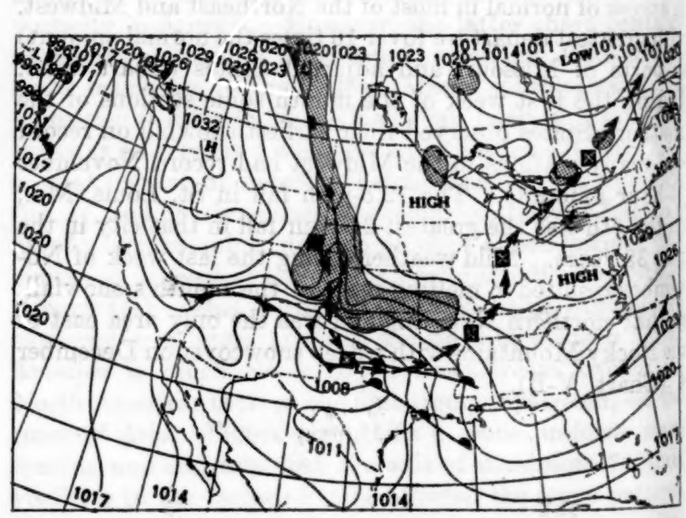

FIGURE 2.—Surface weather chart, 1230 GMT, November 5, 1951. Shading indicates areas of active precipitation. Arrows indicate path of Low. Blocked "X" locates 24-hour positions of Low beginning with 1230 GMT, November 4, 1951.

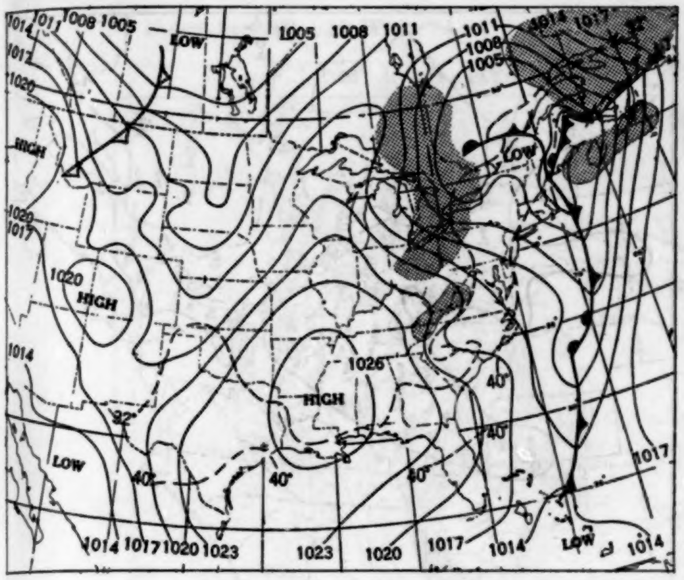

FIGURE 3.—Surface weather chart, 1230 GMT, November 8, 1951. Dotted lines indicate selected isotherms.

ORIGIN OF THE COLD WEATHER

At the surface, cold polar air moved westward across Kansas from the ridge of high pressure to the northeast (fig. 2). Despite the pressure arrangement, the air flow over western Kansas turned sharply left across the surface isobars in reaction to the combined influence of the rising terrain to the west (Colorado and Wyoming) and the area of low pressure near Big Springs, Tex. As time progressed, this blocking and channeling effect of the Rocky Mountains and the increasing influence, upon the circulation, of the deepening Low resulted in a considerable volume of cold air moving southwestward across Oklahoma; eventually it overspread most of Texas. The surface situation was augmented by the deepening trough aloft which continued to transport cold air to more southerly latitudes.

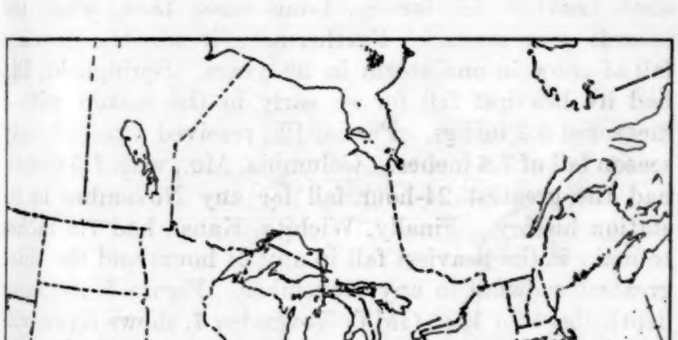

FIGURE 4.—Minimum temperature chart for selected stations during the period November 6–9, 1951. Underlined value indicates new record established.

For 15 hours, after the time of figure 2, cold air from the receding ridge continued to drain into the north and west sides of the developing storm. By late evening on the 7th most of Texas was reporting barometer readings above 1,013 mb. After this period the flow of air from the ridge became less important as air from the Colorado-Wyoming region began draining into Oklahoma and western Texas, under the influence of the 700-mb. flow.

It is worth noting that the 700-mb. flow over the portion of the States just west of the Divide is fairly close to the surface of the earth. On the morning of the 6th, the circulation was such that the same isopleth of height above San Antonio, Tex., could be traced through Amarillo, Tex., Denver, Colo., and Casper, Wyo., to the vicinity of Great Falls, Mont. This same morning the surface ridges of high pressure extended along a line from Montana southeastward through Colorado in a narrowing, central isobar-enclosed area which projected down the Rio Grande Valley to Brownsville, Tex. At 1230 GMT, on the 6th a closed center of pressure (1,029 mb.) formed near Del Rio, Tex.

In the following 2 days the storm moved toward the northeast. (See track, fig. 2.) The drainage of cold air, now from the Mountain States, continued to feed into the Texas area without the Del Rio High showing any definite tendency to move far from its point of origin. Finally, the High began to move eastward (see Chart X), increased in size (fig. 3) and was attended by unseasonably cold weather over Texas and the Gulf States (fig. 4). The low temperatures in Missouri were caused, primarily, by radiation abetted by the deep snow cover.

The history of this High and its associated cold weather departed from the usual story of cold surges coming down directly from the Canadian Plains. Instead, in this instance, a High originated over Alberta, Canada, and then moved southward to southeastern Colorado, where it remained almost stationary for a few days. It became so diffuse as to escape detection after the morning position of November 4. (See Chart IX.) However, the cold air mass, which had been imported, remained in the region until it moved out as has been previously discussed.

The increasing size of the ridge once it became migratory is connected with the equatorward motion of cold air on the west side of the trough aloft which flattened in amplitude as it moved northeastward. As the amplitude decreased the air flow above the cold air mass became more westerly resulting in a fanning out of the cold mass to the east.

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THE SNOWFALL

The first indication that "weather" was brewing over the Southwest was the start of a light snowfall over western Kansas as the cold air moved upslope over that State. As the developing storm moved eastward the upslope motion of the cold surface air ceased and, instead, air from the Gulf began moving over the wedge of polar air to supply the necessary moisture. Missouri and Illinois received the brunt of the fall although such regions as the Great Lakes and the Ohio Valley received snow for varying lengths of time before it changed to rain.

The question suggested is why these two States should receive the heaviest falls of snow. Some clues to the answer are already available from the path of the storm (fig. 2) and the fact that it occluded near Evansville, Ind. As the occluded center moved northeastward the surface circulation in advance of its path pulled warmer and warmer air farther north or northwest (west of the Appalachian Mountains) around the advancing front.

In addition, polar air from the ridge along the Atlantic Coastal Plain, becoming increasingly more maritime in character, fed into the strong circulation on the west side of the mountains. This air stream reached farther to the northwest than the air stream from the Gulf. For instance, it was easily traced from its point of entry on the Maryland shore, across Pennsylvania and Ohio, to southern Michigan. The temperature of the air stream over Michigan was in the low to middle thirties. As the storm swept over the Ohio Valley and the lower Great Lakes the snow changed to rain.

The preceding paragraphs are meant to convey the idea that the snow stopped as the continental polar air, which originally had a trajectory from the northeast, changed to a direction from the southeast bringing in more modified air. This becomes quite clear if one surveys the series of maps for the period. In such a survey it becomes apparent that Missouri and Illinois were at all times in the cold polar air. As the upper trough moved into this region the depth of the cold air increased.

The heavy snowfall broke records for depth at a number of stations in the two States. Springfield, Mo., reported 14.1 inches which presumably was of record proportions for November although the Station Meteorological Summary did not specifically mention the fact. St. Louis, Mo., recorded 12.5 inches, which was the heaviest November snow fall of the station's history. It ranked as the sixth heaviest fall for St. Louis since 1884, when the records were started. Furthermore, it was the heaviest fall of snow in one storm in 39 years. Springfield, Ill., had its heaviest fall for so early in the season with a measured 8.2 inches. Peoria, Ill., received a record early season fall of 7.8 inches. Columbia, Mo., with 7.5 inches, had the greatest 24-hour fall for any November in its station history. Finally, Wichita, Kans., had 7.5 inches to make it the heaviest fall in any 24 hours and the third greatest snowfall in any November. Figure 5, the snow depth chart for 1230 GMT, November 7, shows representative values for the amount of snow cover during the period of November 6 to 8.

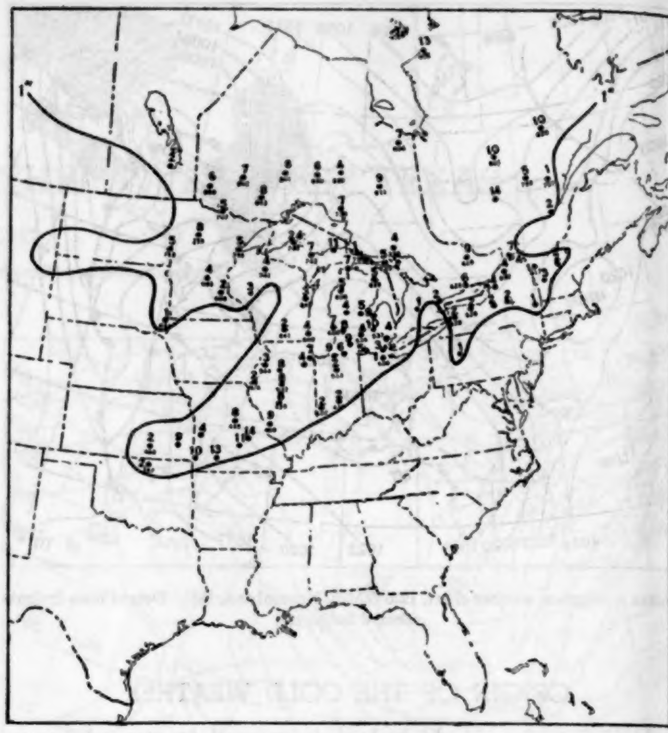

FIGURE 5.—Snow depth chart, 1230 GMT, November 7, 1951, showing the depth of the snow on the ground (in inches) at observation time.

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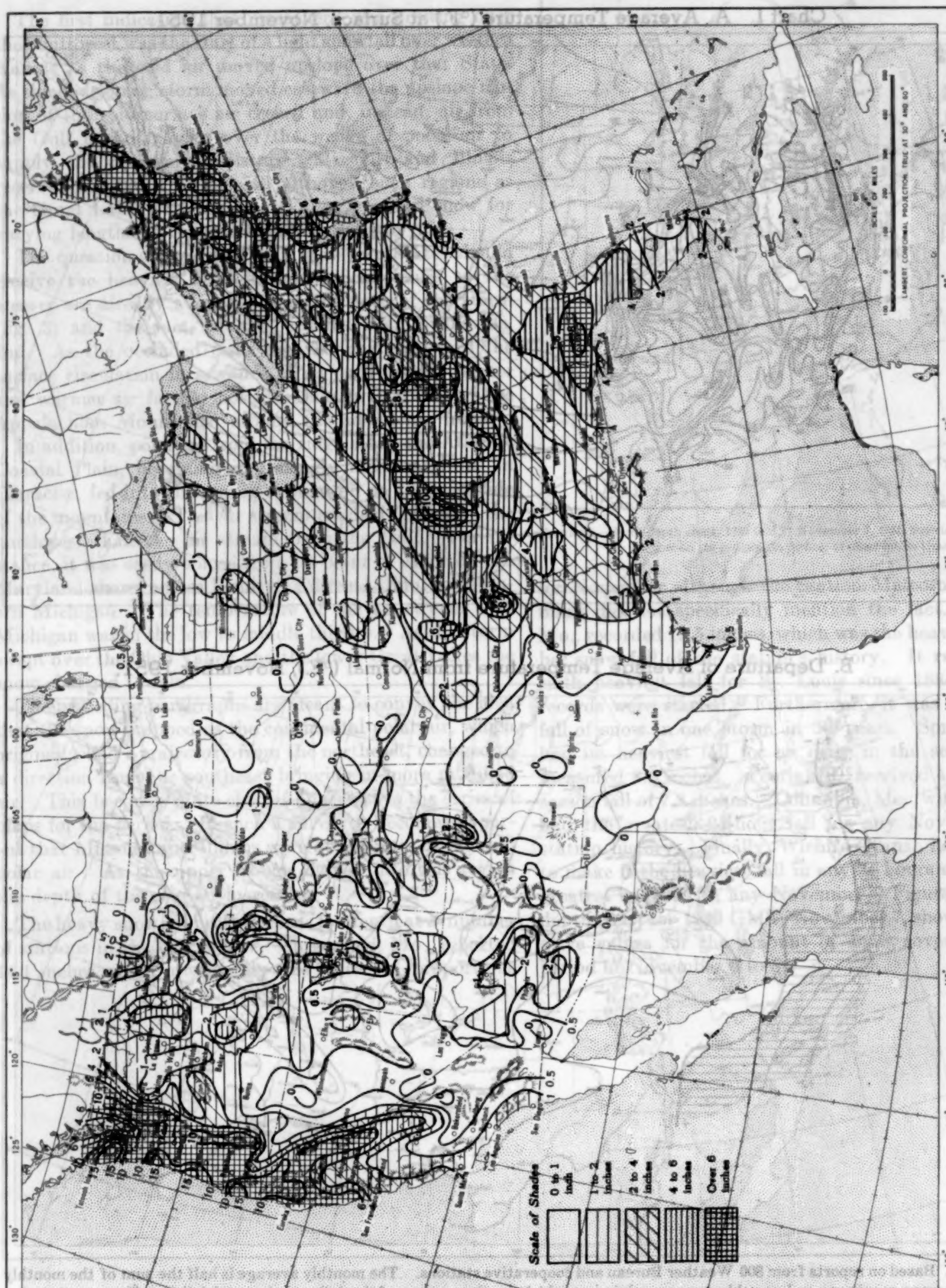
Chart I. A. Average Temperature (°F.) at Surface, November 1951.

B. Departure of Average Temperature from Normal (°F.), November 1951.

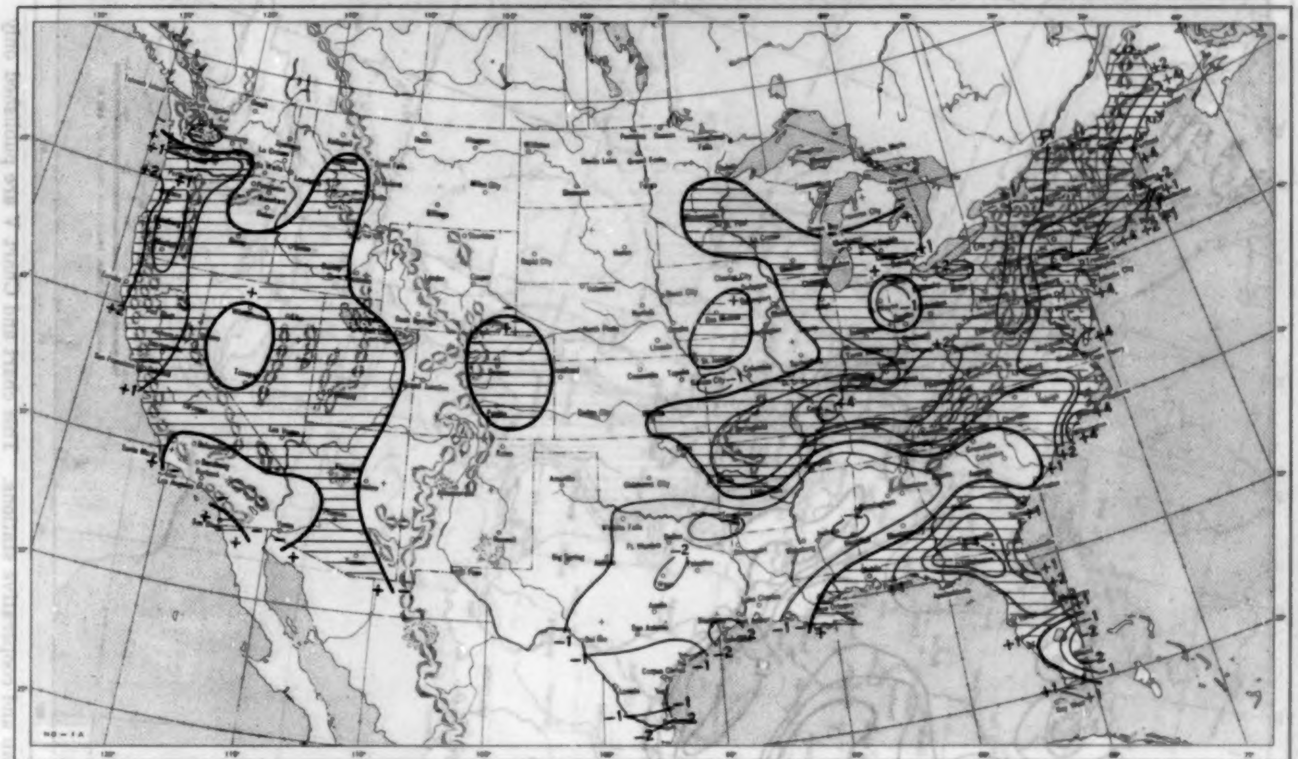
A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), November 1951.

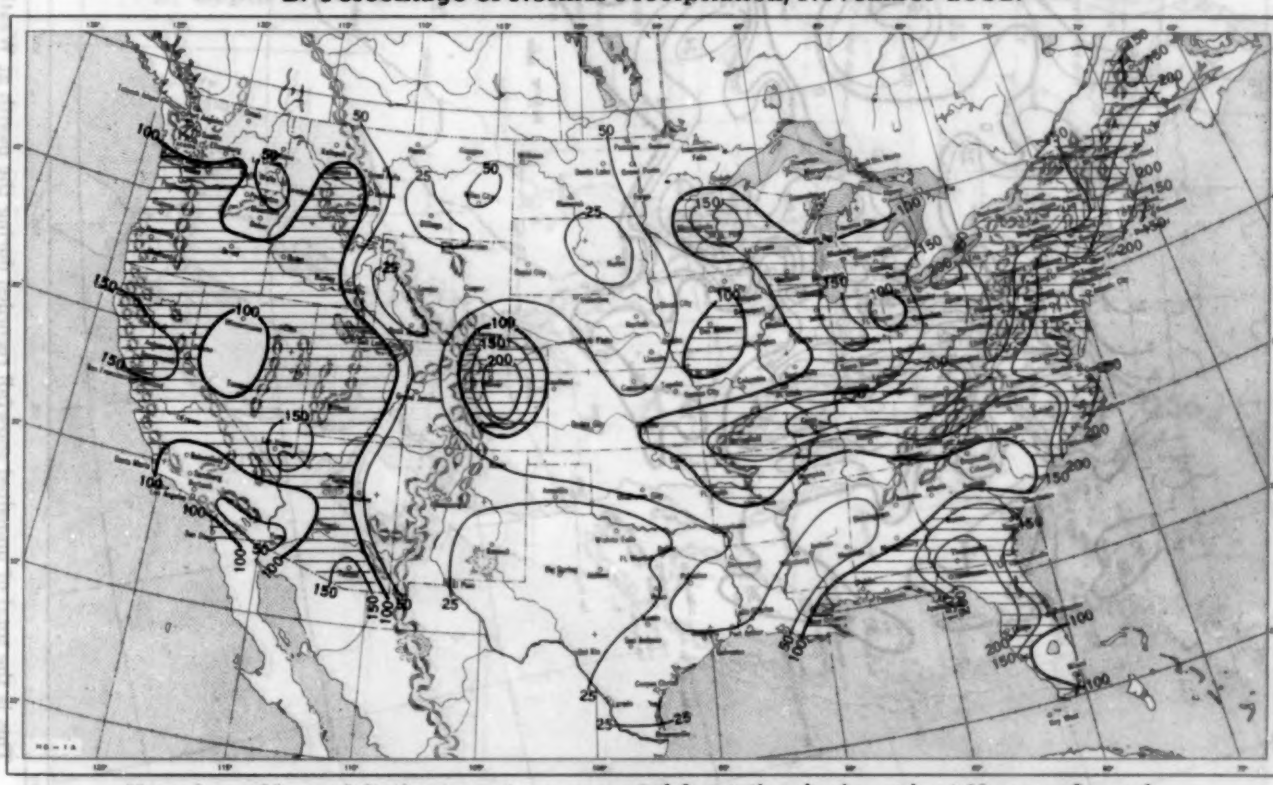


Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), November 1951.

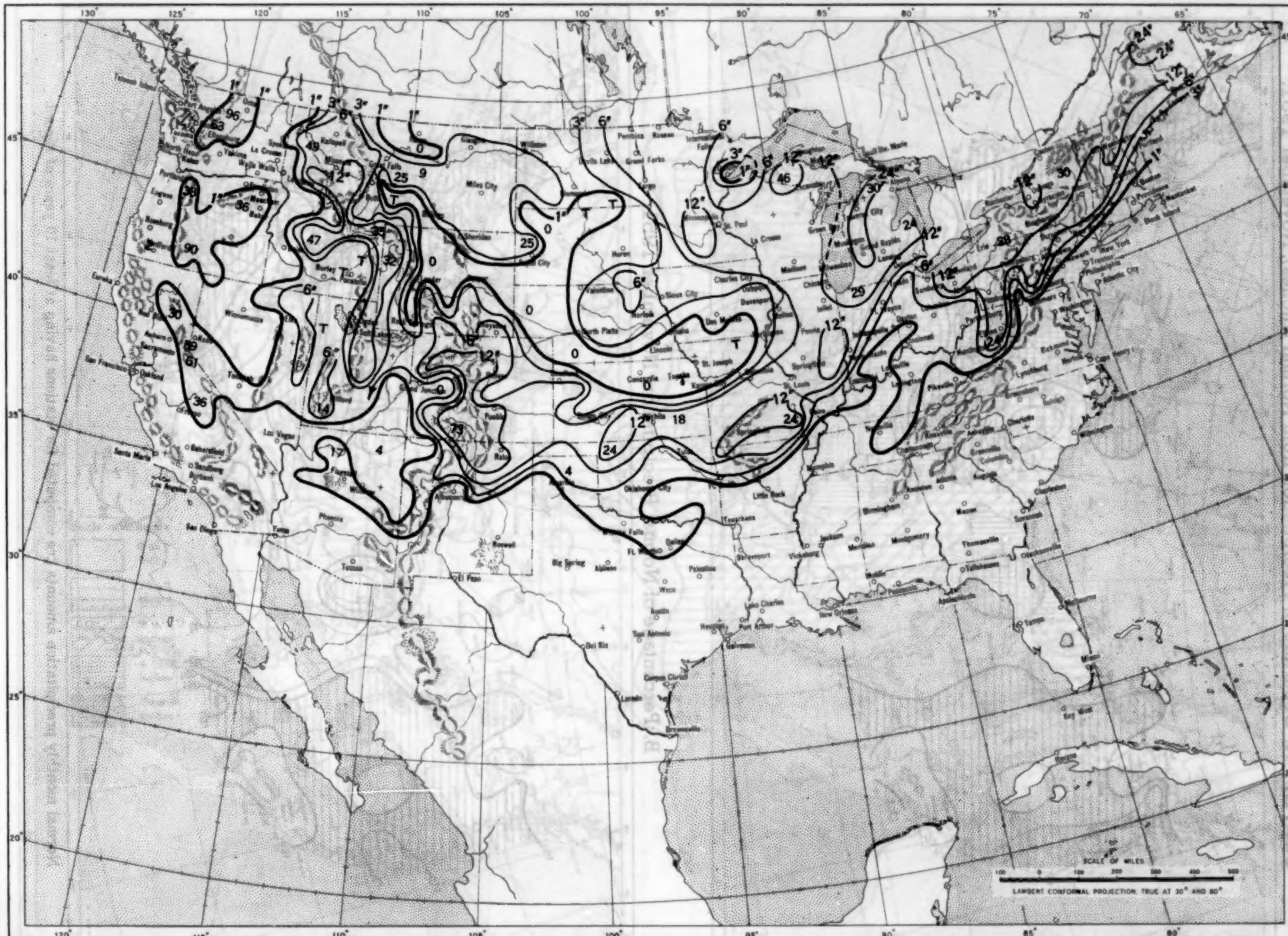


B. Percentage of Normal Precipitation, November 1951.



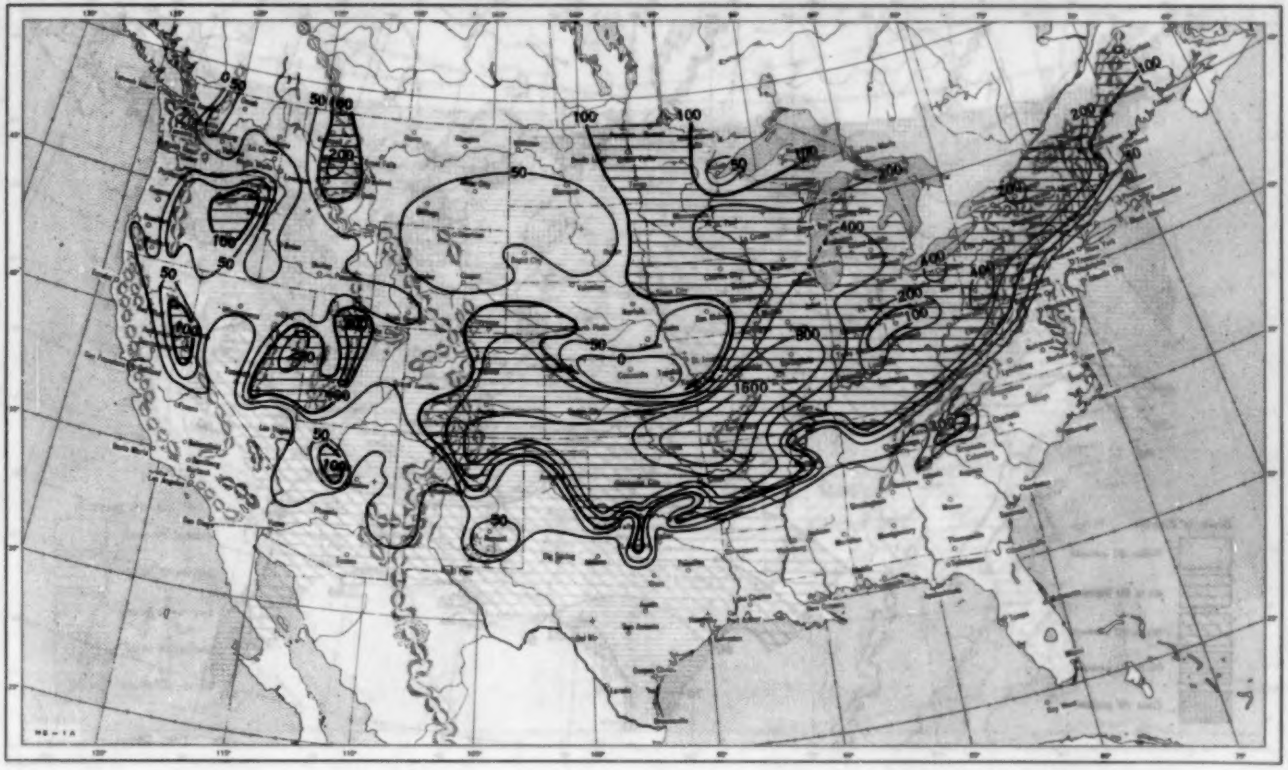
Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart IV. Total Snowfall (Inches), November 1951.

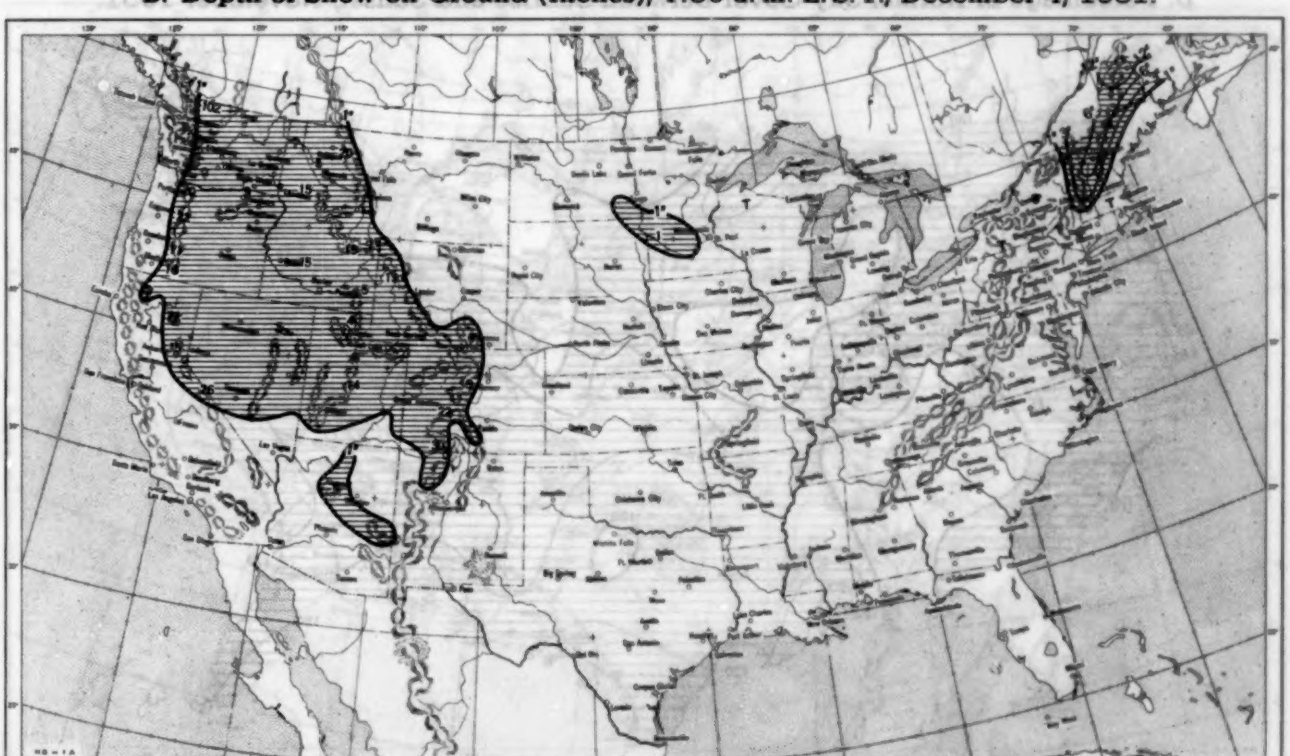


This is the total of unmelted snowfall recorded during the month at Weather Bureau and cooperative stations. This chart and Chart V are published only for the months of November through April although of course there is some snow at higher elevations, particularly in the far West, earlier and later in the year.

Chart V. A. Percentage of Normal Snowfall, November 1951.

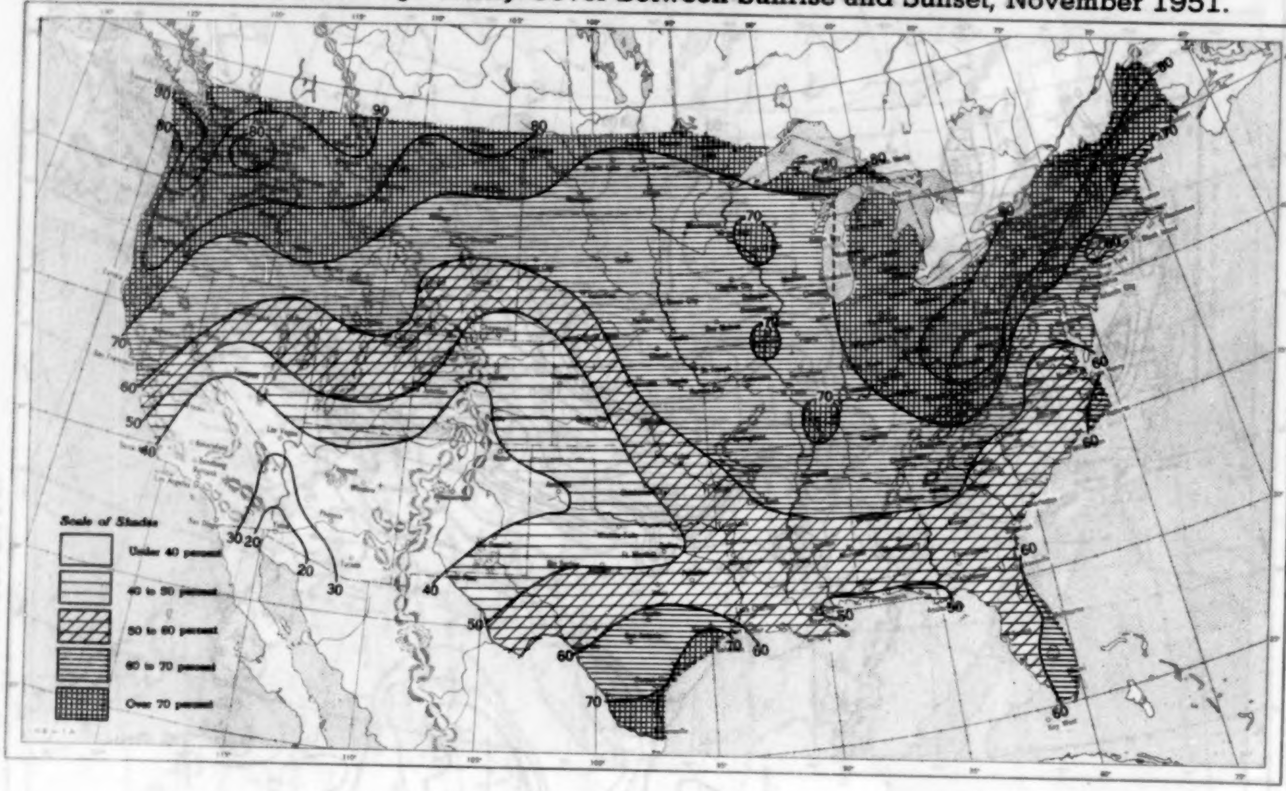


B. Depth of Snow on Ground (Inches), 7:30 a. m. E. S. T., December 4, 1951.

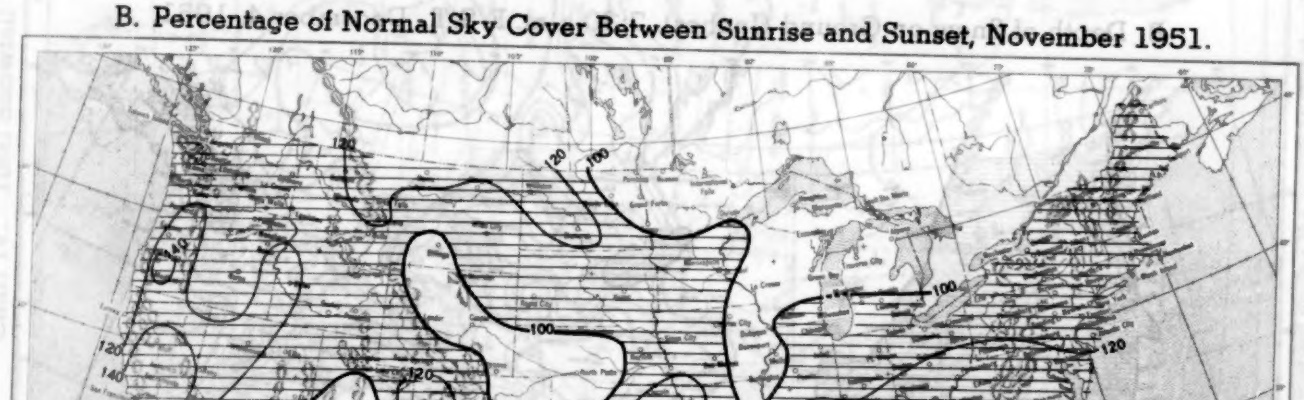


A. Amount of normal monthly snowfall is computed for Weather Bureau stations having at least 10 years of record. B. Shows depth currently on ground at 7:30 a. m. E.S.T., of the Tuesday nearest the end of the month. It is based on reports from Weather Bureau and cooperative stations. Dashed line shows greatest southern extent of snowcover during month.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, November 1951.

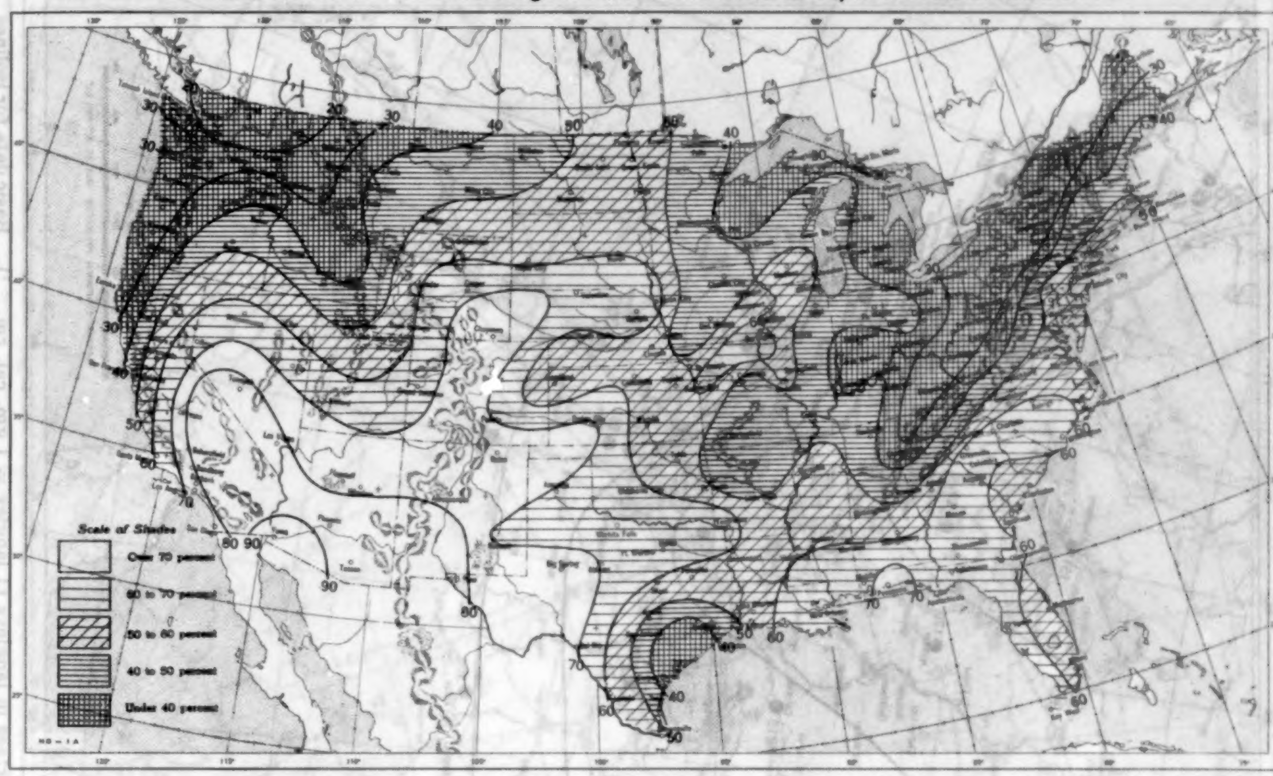


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, November 1951.



A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, November 1951.



B. Percentage of Normal Sunshine, November 1951.

A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, November 1951. Inset: Percentage of Normal Average Daily Solar Radiation, November 1951.

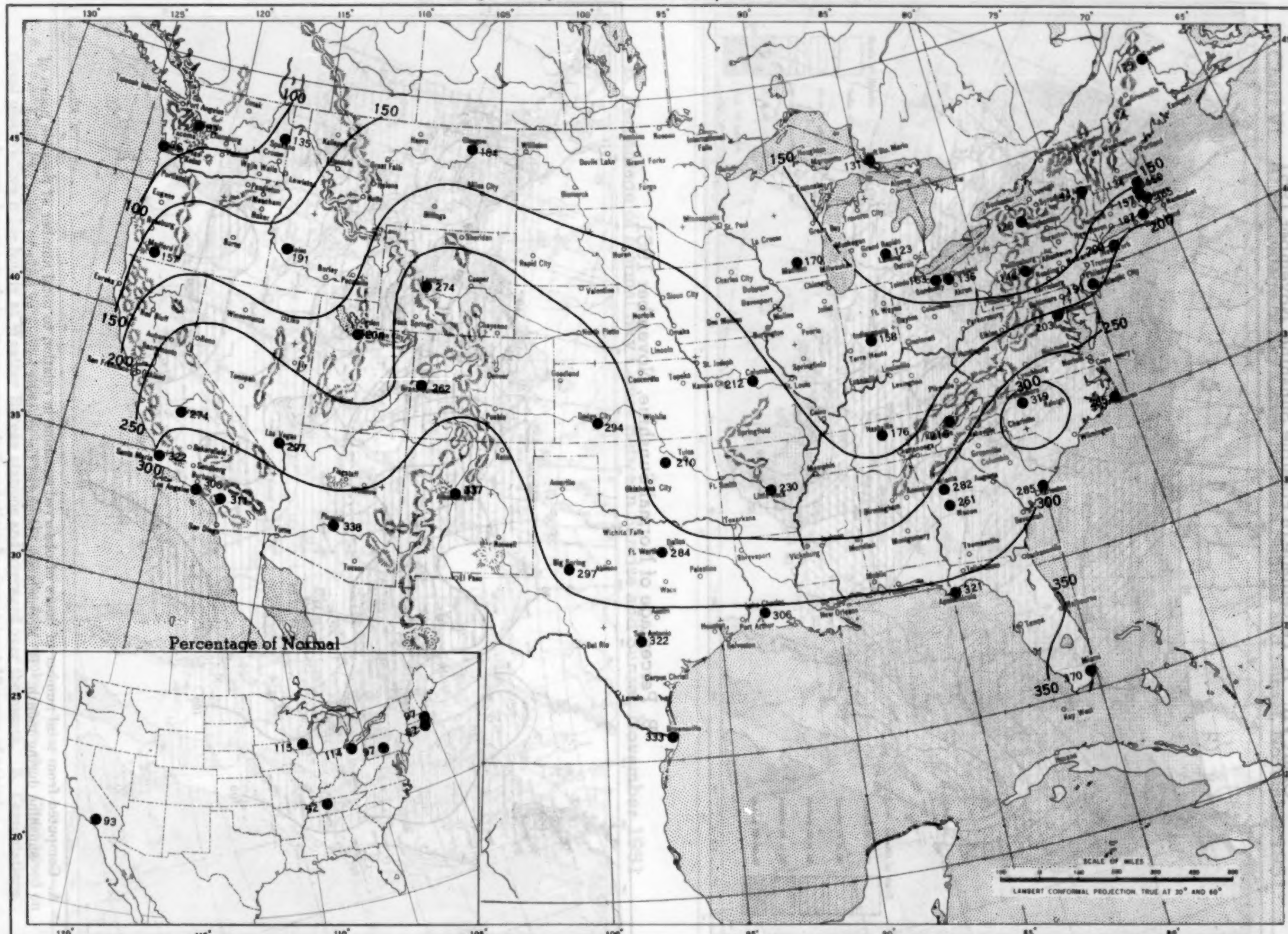
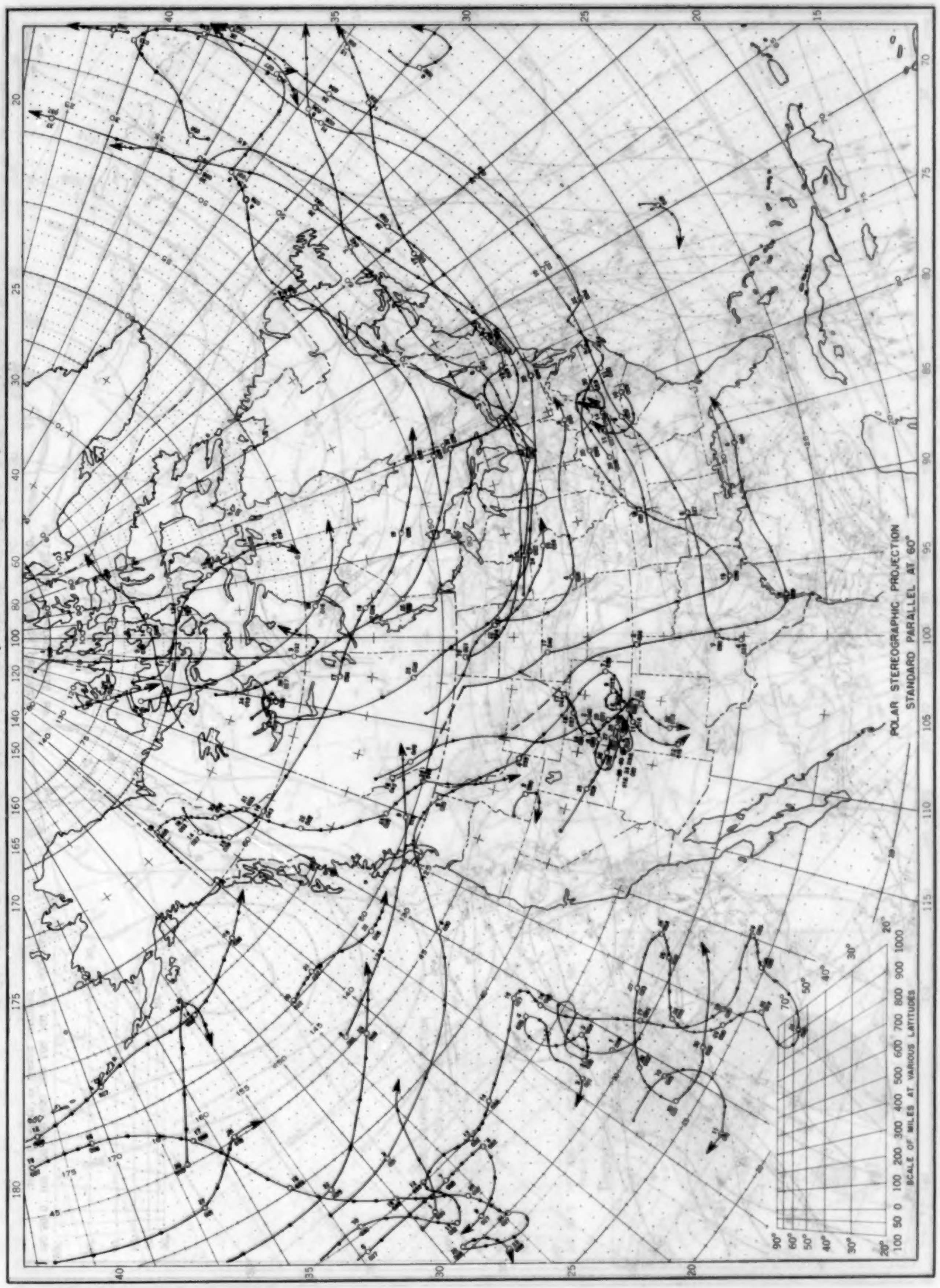


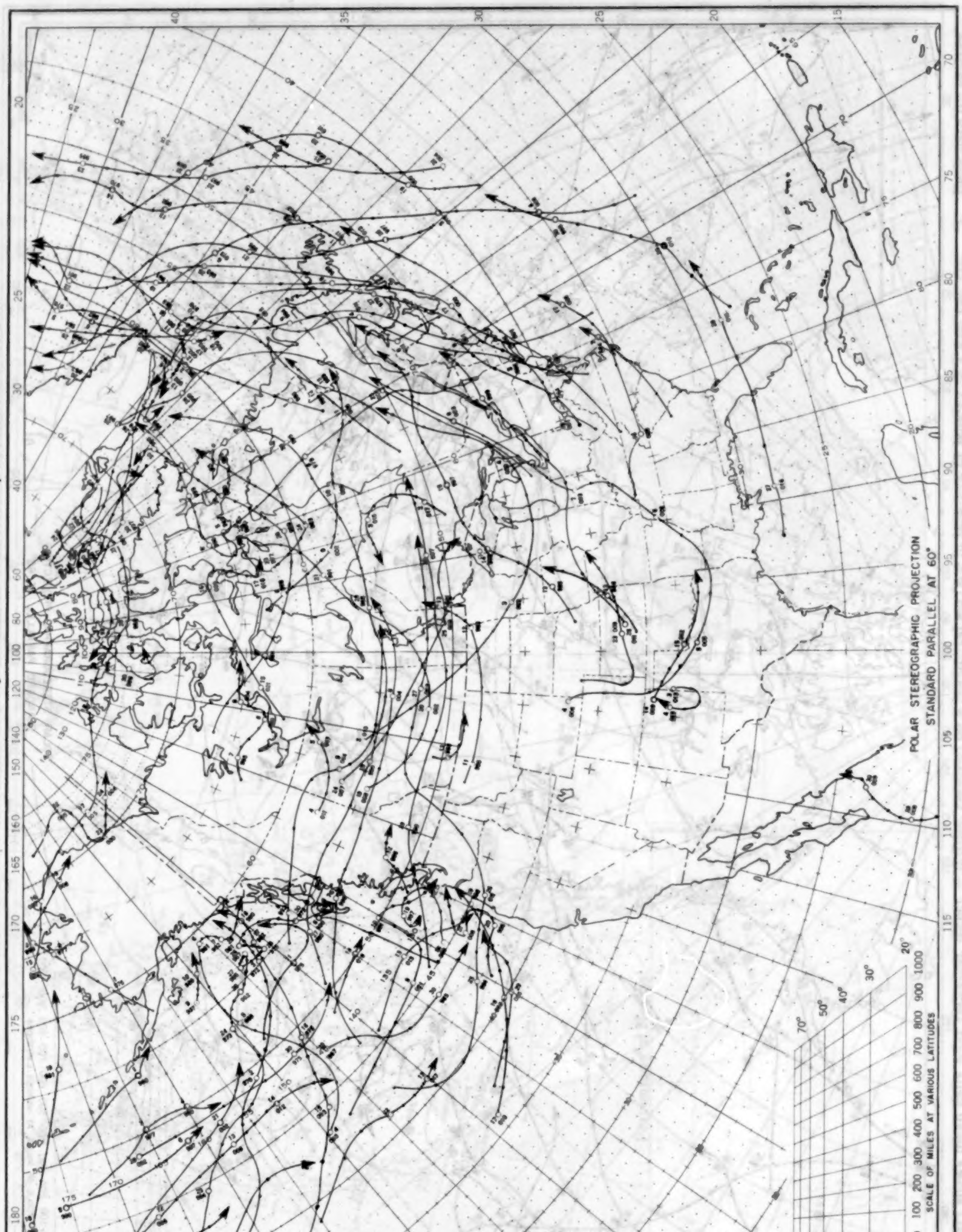
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm.$^{-2}$). Basic data for isolines are shown on chart. Further estimates obtained from supplementary data for which limits of accuracy are wider than for those data shown. Normals are computed for stations having at least 9 years of record.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, November 1951.



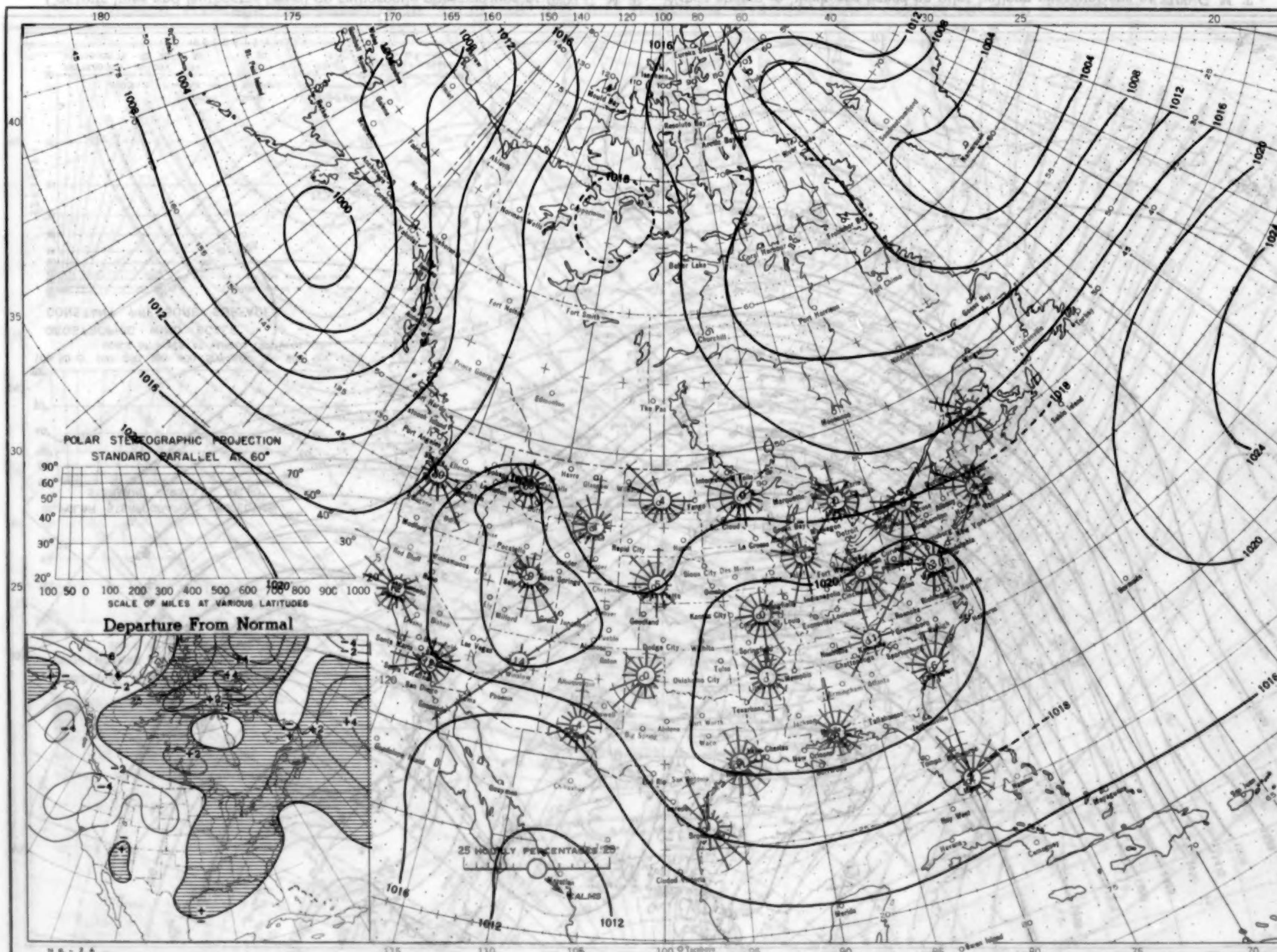
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, November 1951.



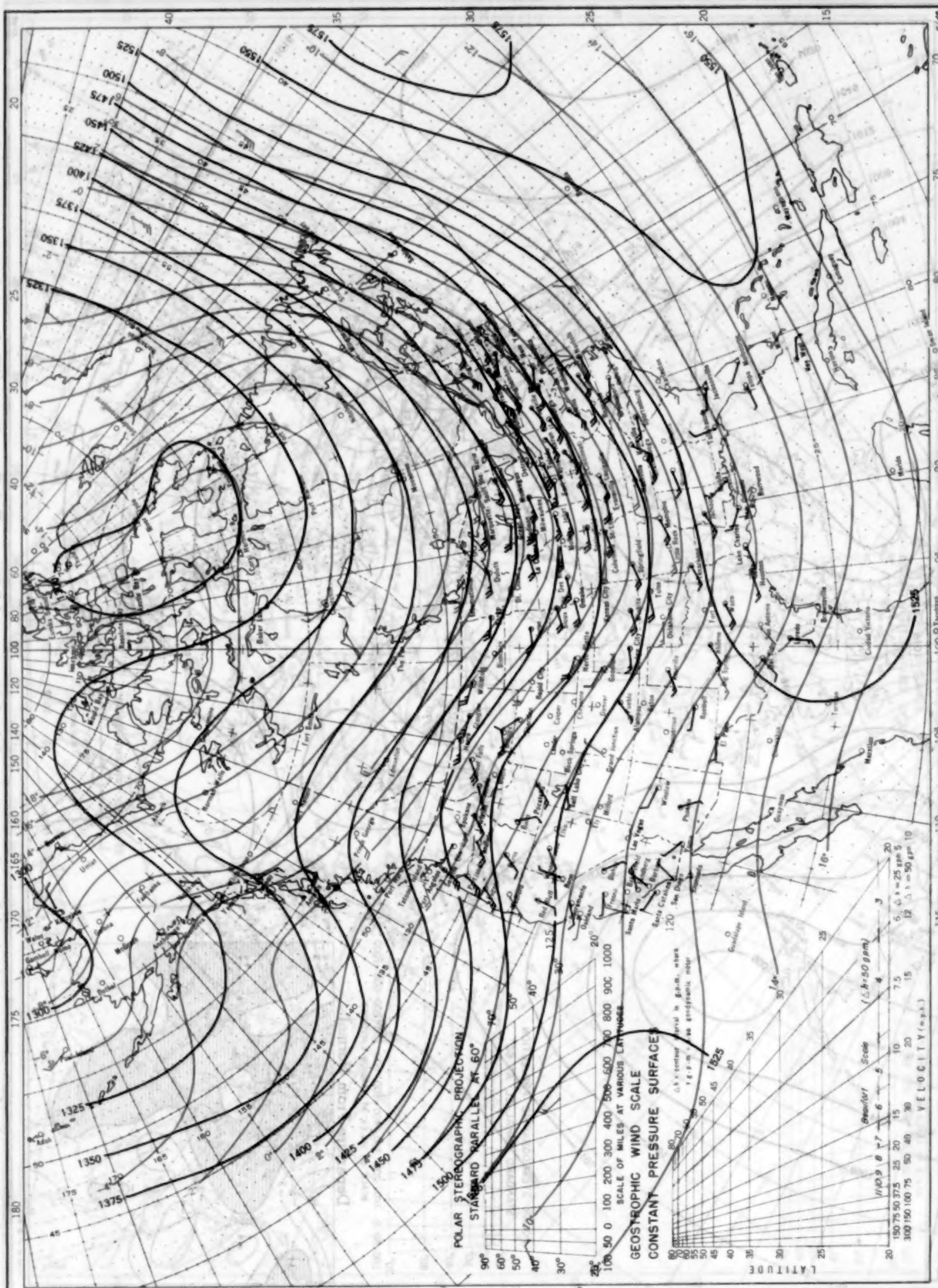
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, November 1951. Inset: Departure of Average Pressure (mb.) from Normal, November 1951.



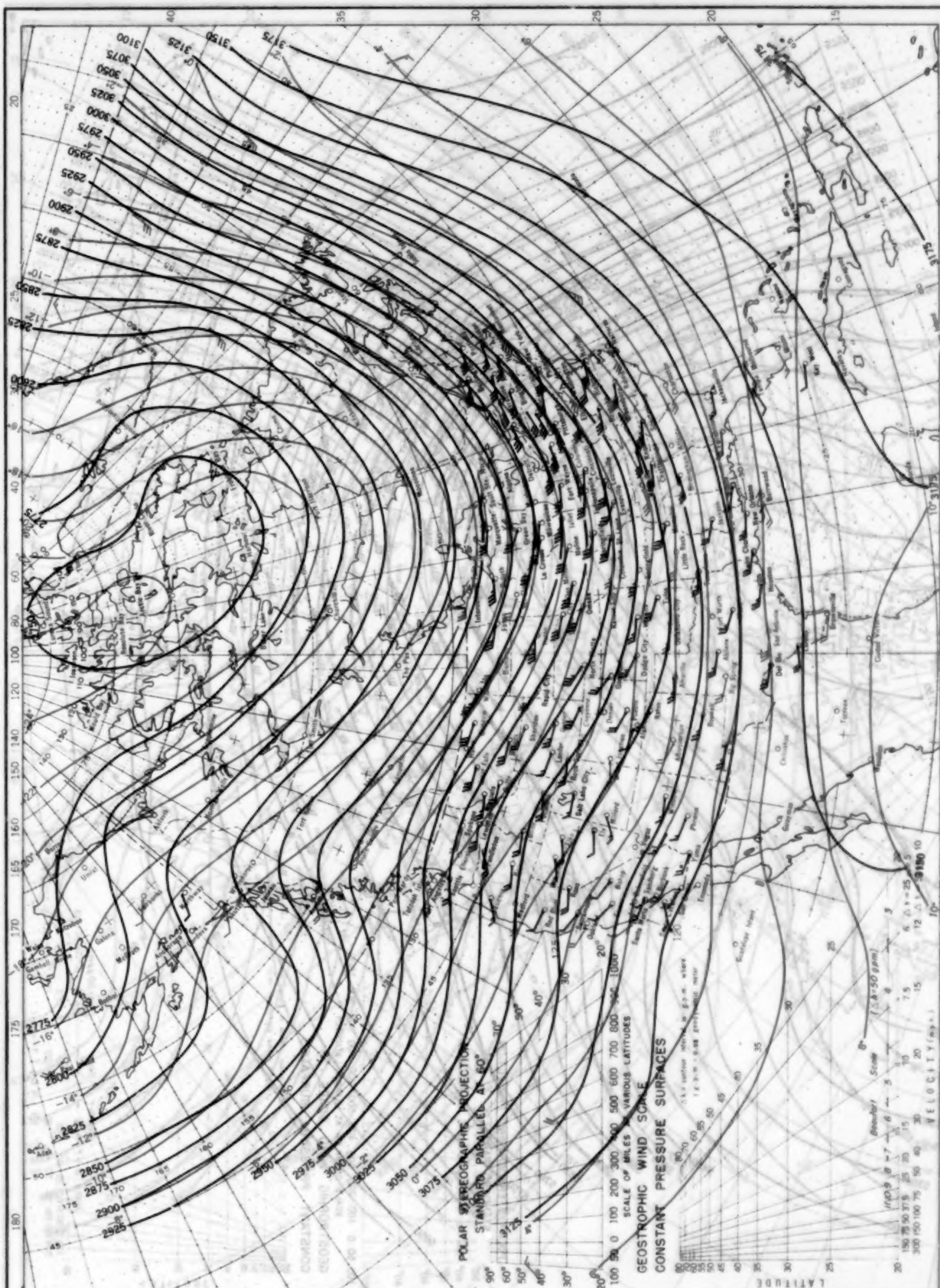
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), November 1951.



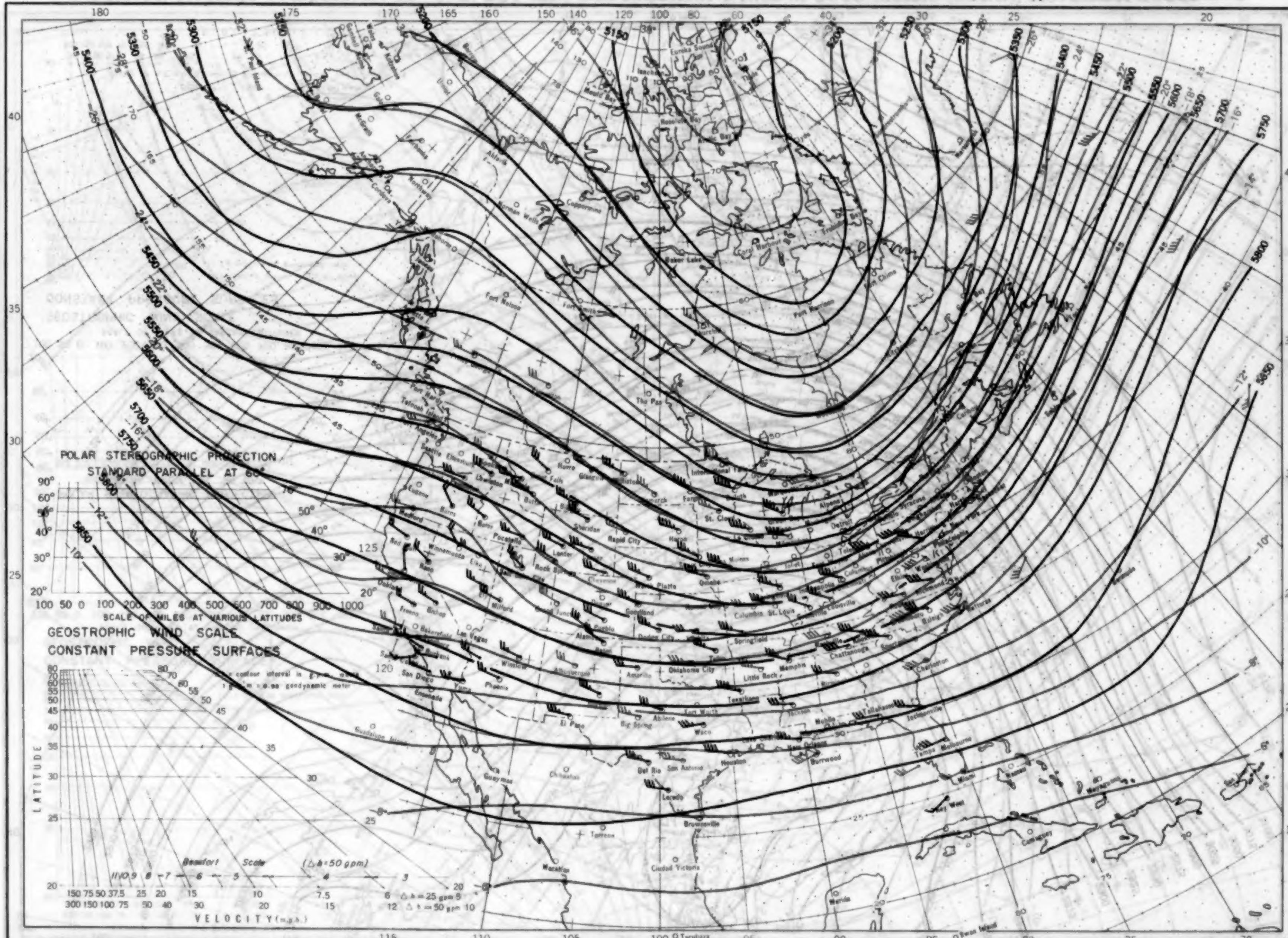
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), November 1951.



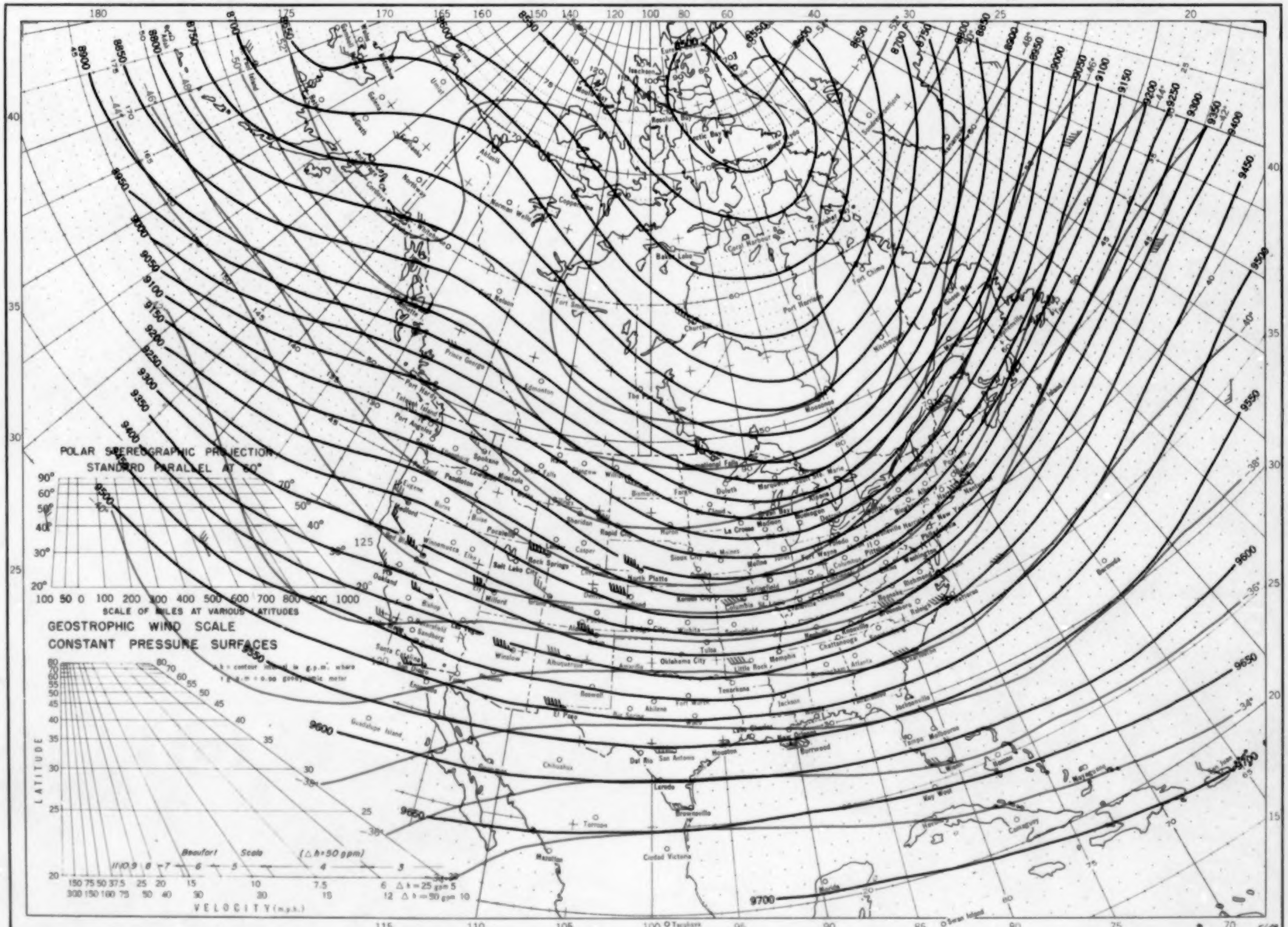
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C. at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), November 1951.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), November 1951.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.